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ARPA-E MACROALGAE VALORIZATION WORKSHOP

Transitioning to Green Fertilizers in Agriculture: Outlook and Opportunities

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Cost Targets and Formulations for Common Ag Fertilizers:

- Price targets should be based on retail fertilizer prices minus actual transportation, storage costs, and retail margins
- Since green fertilizer production may be localized, retail (not plant gate) rates may be used as a basis
- Keep in mind, conventional fertilizer pricing can move lower with competition
- Pricing is highly volatile based on natural gas and grain prices
- Since there are limited policies and market pressures, no current premiums for green fertilizers are available
- Typical transportation and storage cost is ~ $100 / ton
- Typical retail margin is ~ 22%

US Retail Agricultural Fertilizer Prices

Common Fertilizer Types	N-P-K or Percent Available	Retail Price / Short Ton[1]
Anhydrous Ammonia (NH_3)	82-0-0	$450
Urea	46-0-0	$360
UAN 28% Liquid	28-0-0	$275
MAP	11-52-0	$455
DAP	18-46-0	$430
Potash	0-0-60	$330
Sulfur	90%	$1,000
Zinc	35%	$2,000
Boron	12%	$2,000

[1](11/10/2020 retail prices from a Minnesota ag cooperative)

Estimated US Agriculture Fertilizer Market for Major Crops

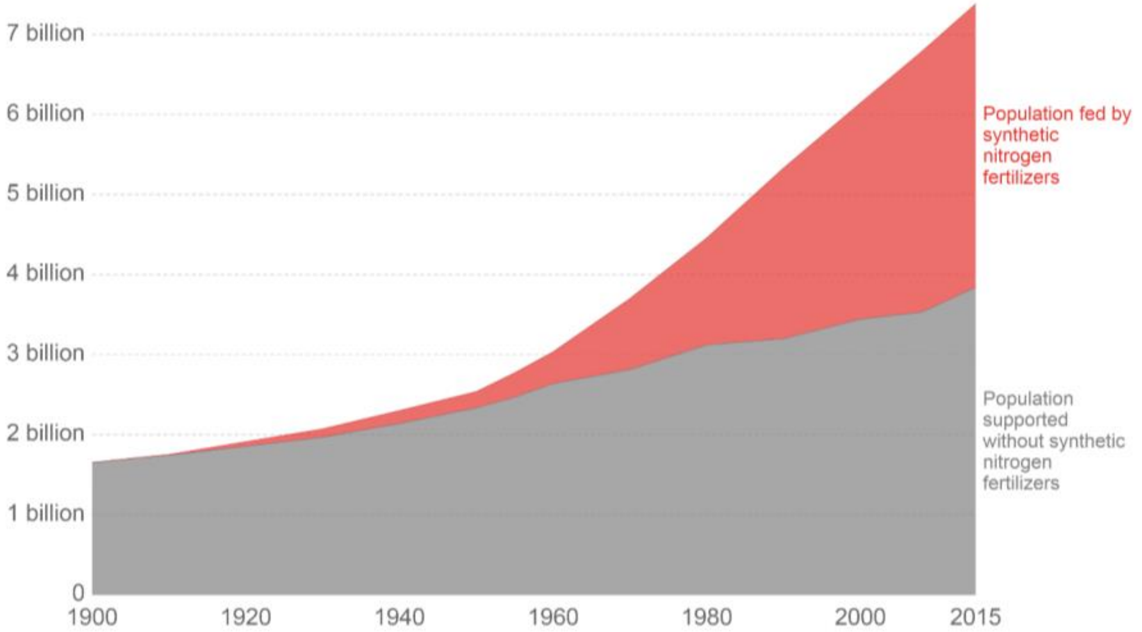
Crop	Acres planted in US[1] (in millions)	Est. Nutrient Requirement/ ac N-P-K-S-Zn-B	Est. Total N (Short tons)	Est. Total P (Short tons)	Est. Total K (Short tons)	Est. Total S (Short tons)	Est. Total Zn (Short tons)	Est. Total B (Short tons)
Corn	92.0	**180-80-80**-15-1-0	8,280,000	3,680,000	3,680,000	690,000	46,000	0
Soy	83.8	**18-46-60**-10-0-0	754,200	1,927,400	2,514,000	419,000	0	0
Wheat	44.3	**80-40-40**-10-1-0	1,772,000	886,000	886,000	221,500	22,150	0
Cotton	12.2	**80-40-40**-10-1-0.5	488,000	244,000	244,000	61,000	6,100	3050
Alfalfa	11.7	**0-90-90**-10-0-1	0	526,500	526,500	58,500	5,850	5850
FERTILIZER RETAIL VALUE[2]			**$6.2 to $8.1 Billion** (NH3/urea)	**$6.8 Billion**	**$4.3 Billion**	**$1.6 Billion**	**$458 Million**	**$148 Million**

[1]USDA Acreage Report, National Agriculture Statistics Service (NASS), June 30, 2020 ISSN: 1949-1522
[2]A portion of the nutrients will be supplied by livestock manure and other organic fertilizers.

Ammonia Feeds the World

- Backbone of nitrogen fertilizer:

  Anhydrous ammonia (direct application), urea, ammonium nitrate, UAN, …
- Feeds half of the global population



Source: Ritchie, *Our World in Data*: https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed#note-4; Erisman et al., 2008, Nat. Geoscience, 1 (10), 636-639.

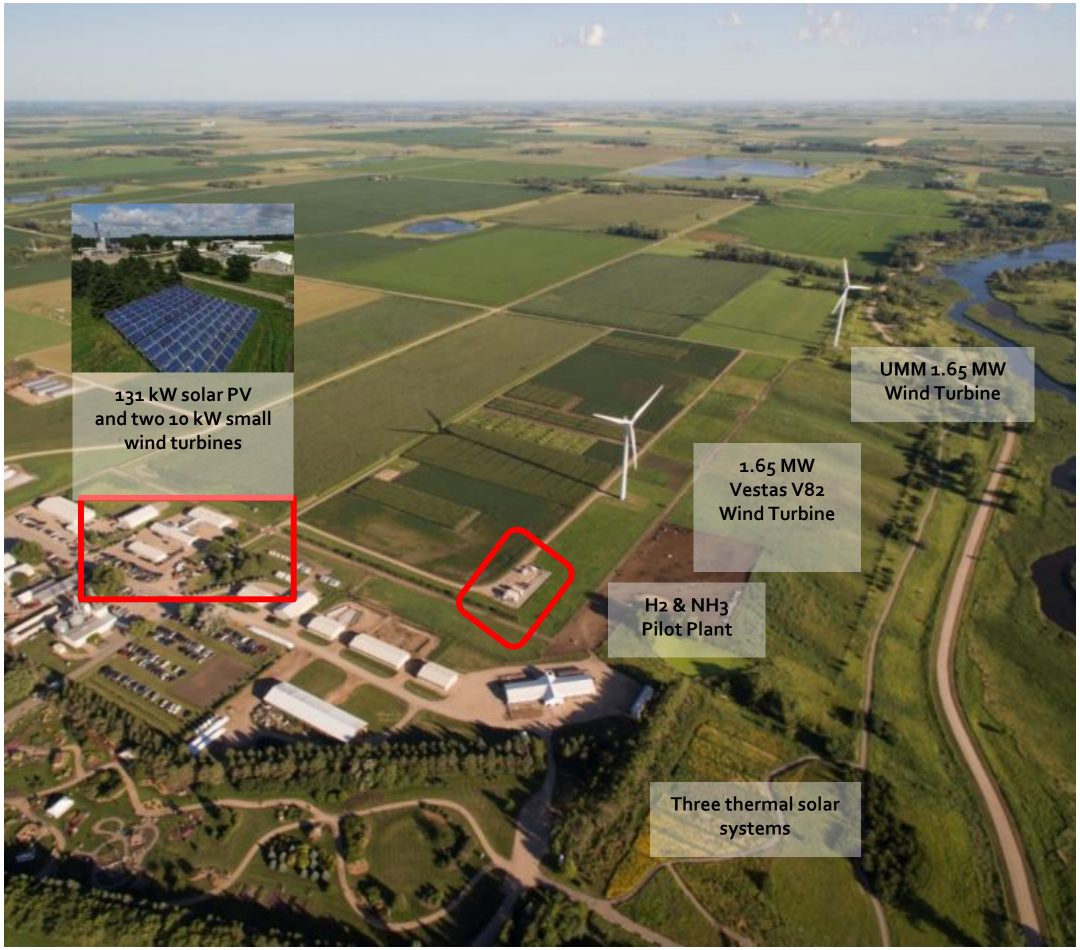
Program Goal: Reduce fossil energy consumption in production agriculture

- 20 to 25 % of GHG in Minnesota and the world attributed to agriculture, forestry, and related industries
  (MPCA, 2016; IPCC, 2017)

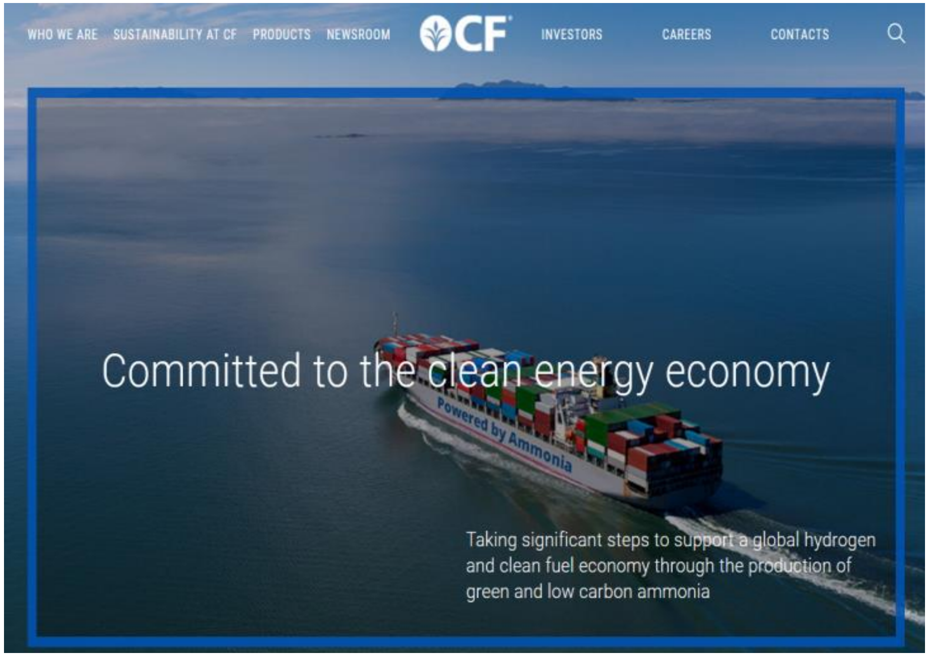
- 1% global GHG emissions attributed to ammonia and nitrogen fertilizer production

- University of Minnesota West Central Research and Outreach Center, Morris, MN

- 1,100 acre agriculture experiment station



Outlook: Green Ammonia



- CF is the world's largest producer of ammonia
- On October 29, 2020, CF announced commitment to decarbonize the world's largest ammonia production network, Establishing carbon emissions reduction targets of:

  -25% reduction by 2030

  -net-zero carbon emissions by 2050
- Green ammonia production -ammonia produced through a carbon-free electrolysis process using renewable electricity

Michèle Azalbert, CEO of ENGIE Hydrogen and Yves Bonte, EVP New Business of Yara at the agreement signing

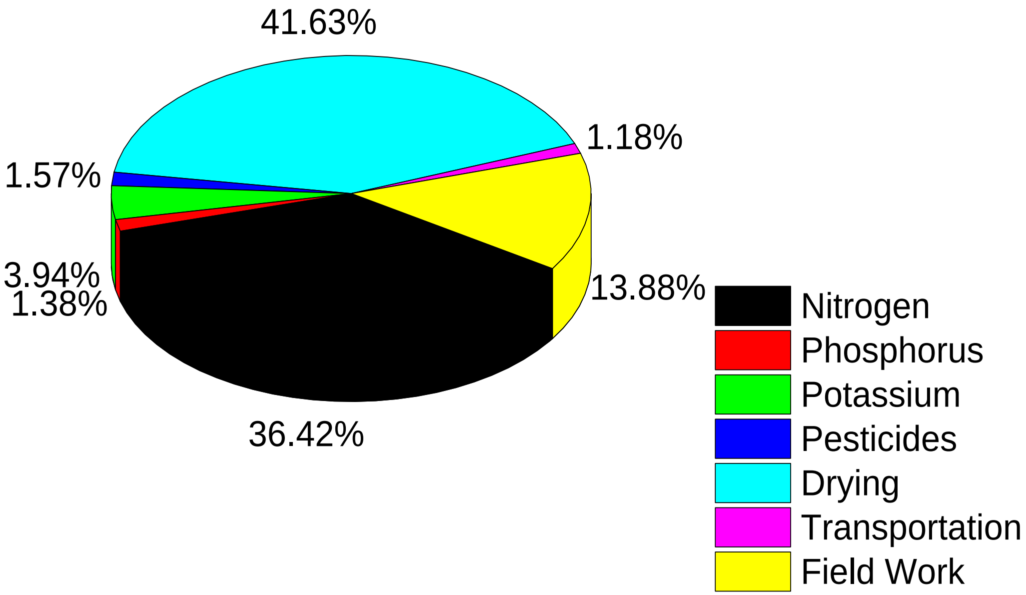
February 13, 2019
Yara and ENGIE to test green hydrogen technology in fertilizer production.
Yara's mission is to responsibly feed the world and protect the planet. In achieving this, innovating sustainable solutions is key.

➢ **Most (if not all) of the world's leading ammonia production, engineering, and technology companies are working on zero-carbon ammonia**

Key Role for Green Ammonia:
Corn production is the backbone of Midwest US agriculture

- Approximately 1.6 MJ of energy consumed to produce one kg of corn
- Results in approximately 6.2 MJ /kg net energy for feed gain (beef)
- Roughly, 1/3 is used for ethanol production and 2/3 for livestock and some export
- Grain drying is the largest single energy consumer in our study
- Nitrogen fertilizer ranks second highest
- N fertilizer has significant impact on the carbon intensity of corn grain and, as a result, many other ag products such as ethanol

Fossil energy footprint of corn production as measured at the West Central Research and Outreach Center – Morris, MN



J. Tallaksen et al., 2016. UMN West Central Research and Outreach Center

Green Ammonia: An Elegant Solution

Wind Energy + Water + Air = Nitrogen Fertilizer

Step 1. Electrolysis of Water $2H_2O \longrightarrow 2H_2 + O_2$

Step 2. Air Separation / Pressure Swing Absorption:

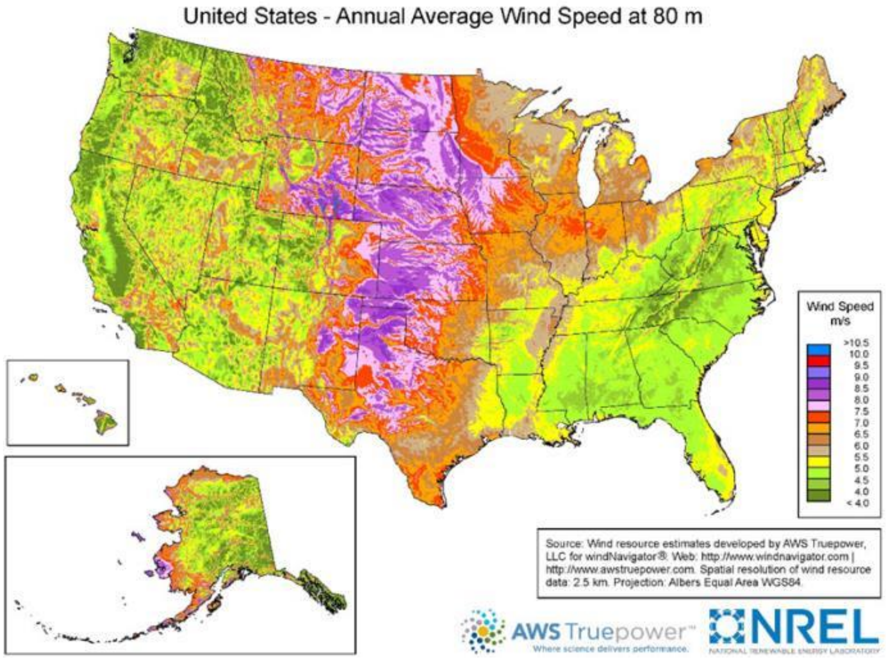
Oxygen (O_2) and argon (Ar) are absorbed in a molecular sieve leaving nitrogen $\longrightarrow N_2$

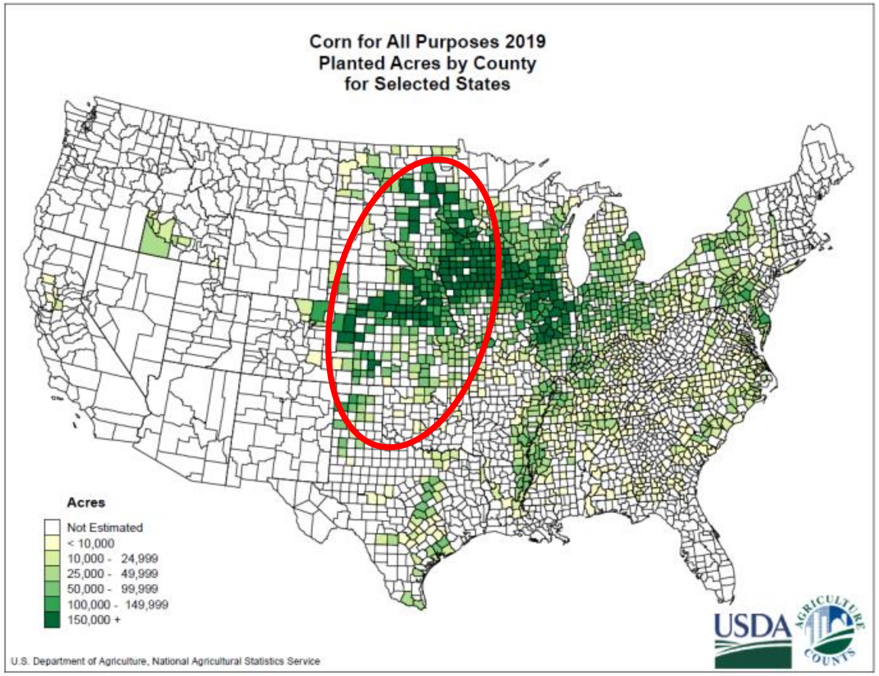
Step 3. Haber or Haber-Bosch Process:

$$N_{2\,(g)} + 3H_{2\,(g)} \rightleftarrows 2NH_{3(g)} \qquad \triangle H = -92.4\ kJ$$

- Wind and solar intermittency can pose a problem for HB processes
- Intermittency can be managed through advanced process controls, additional hydrogen and nitrogen storage, thermal integration and storage, and lower pressure and temperature production processes - heat loss is primary challenge for re-start

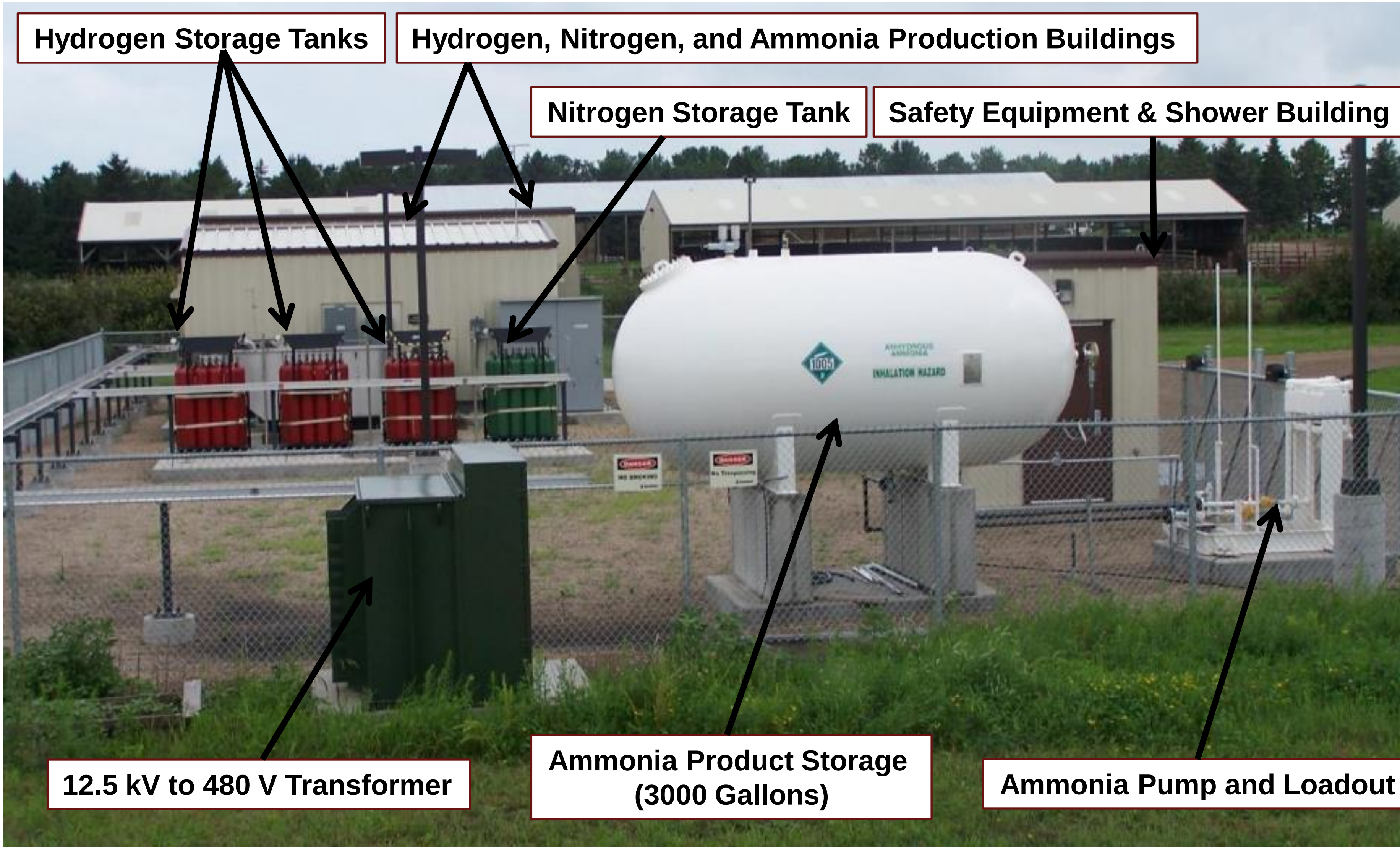
Scale: Green Ammonia





- US wind resource is synergistic with Midwest corn production and nitrogen fertilizer demand – inherently distributed
- US nitrogen fertilizer demand could be met with approximately 50,000 MW of nameplate wind energy capacity – current US wind generation is 105,583 MW of nameplate capacity
- Opportunity to utilize “stranded” wind and solar resources (and excess nuclear)
- New technology and-/-or policy is needed for green N fertilizer to compete

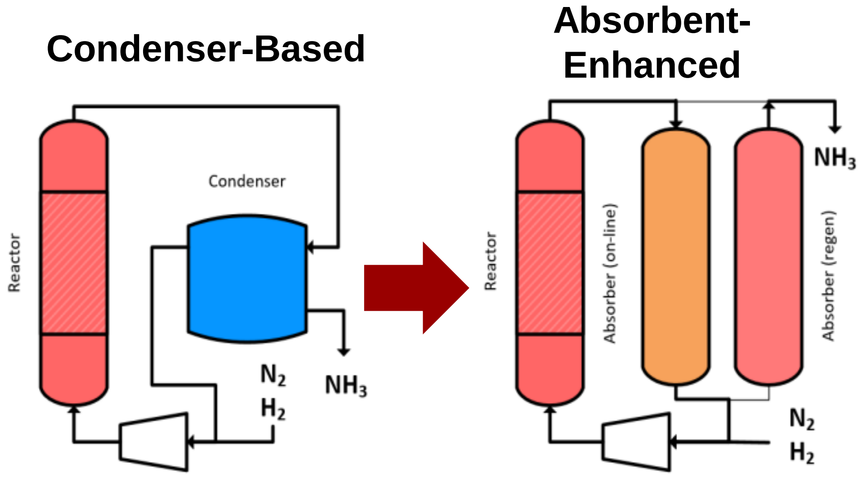
U of MN Renewable Hydrogen and Ammonia Pilot Plant

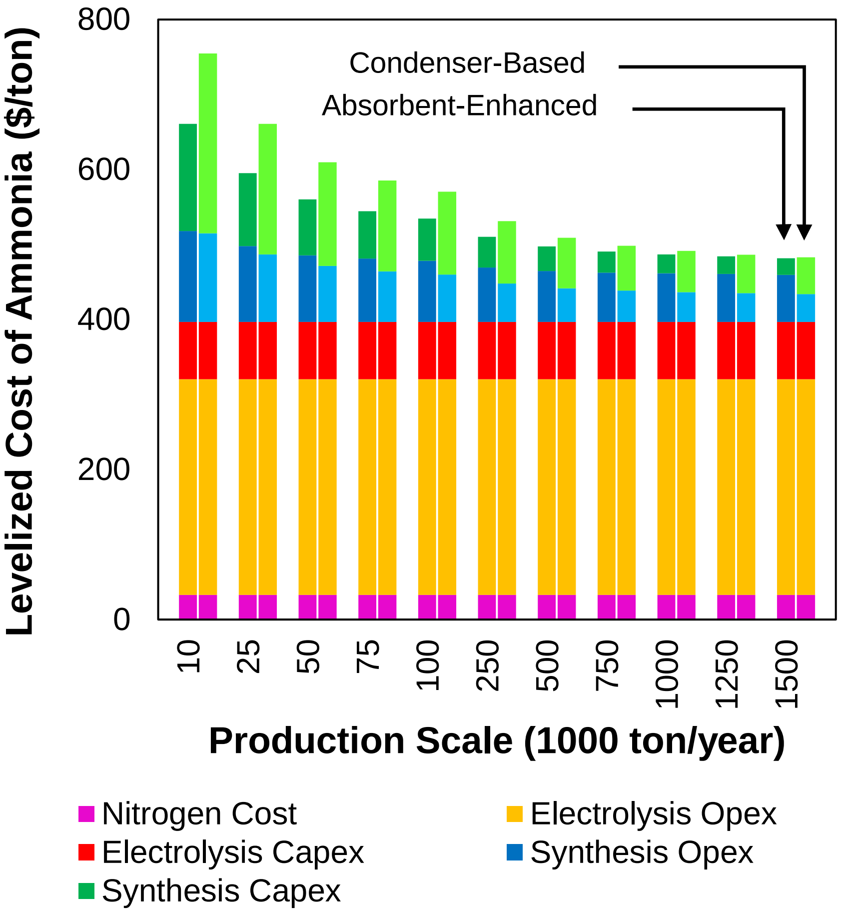


Renewable ammonia for fertilizer:

Comparison of Absorbent-Enhanced and Condenser-Based Processes

Palys et al. (2019). *AIChE Annual Meeting 2019*, Orlando, FL.





- Lower pressure
- Hotter separation

Absorbent-enhanced process:

- Lower capital investment (~40%)
- Higher energy consumption due to heat needed for desorption (no integration)
- **Less expensive (~ 25%) synthesis at small production scales!**

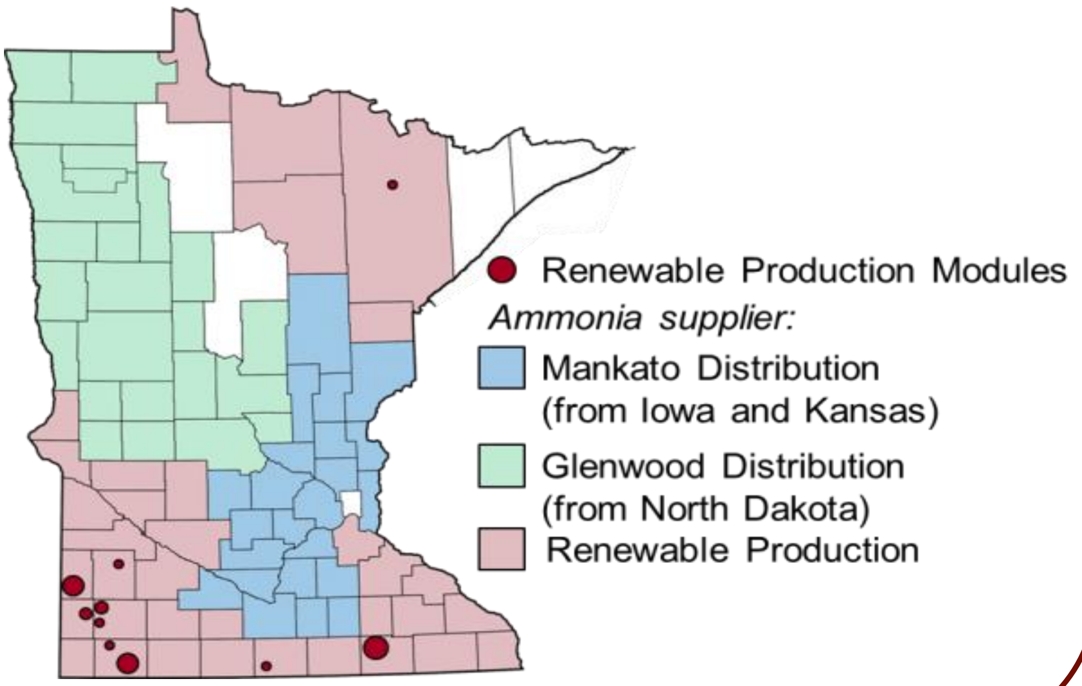
Wind-Powered Ammonia Production Optimal Facility Location

Palys et al. (2019). *Ind. Eng. Chem. Res. 58 (15)*, 5898-5908.

Our vision for regional deployment

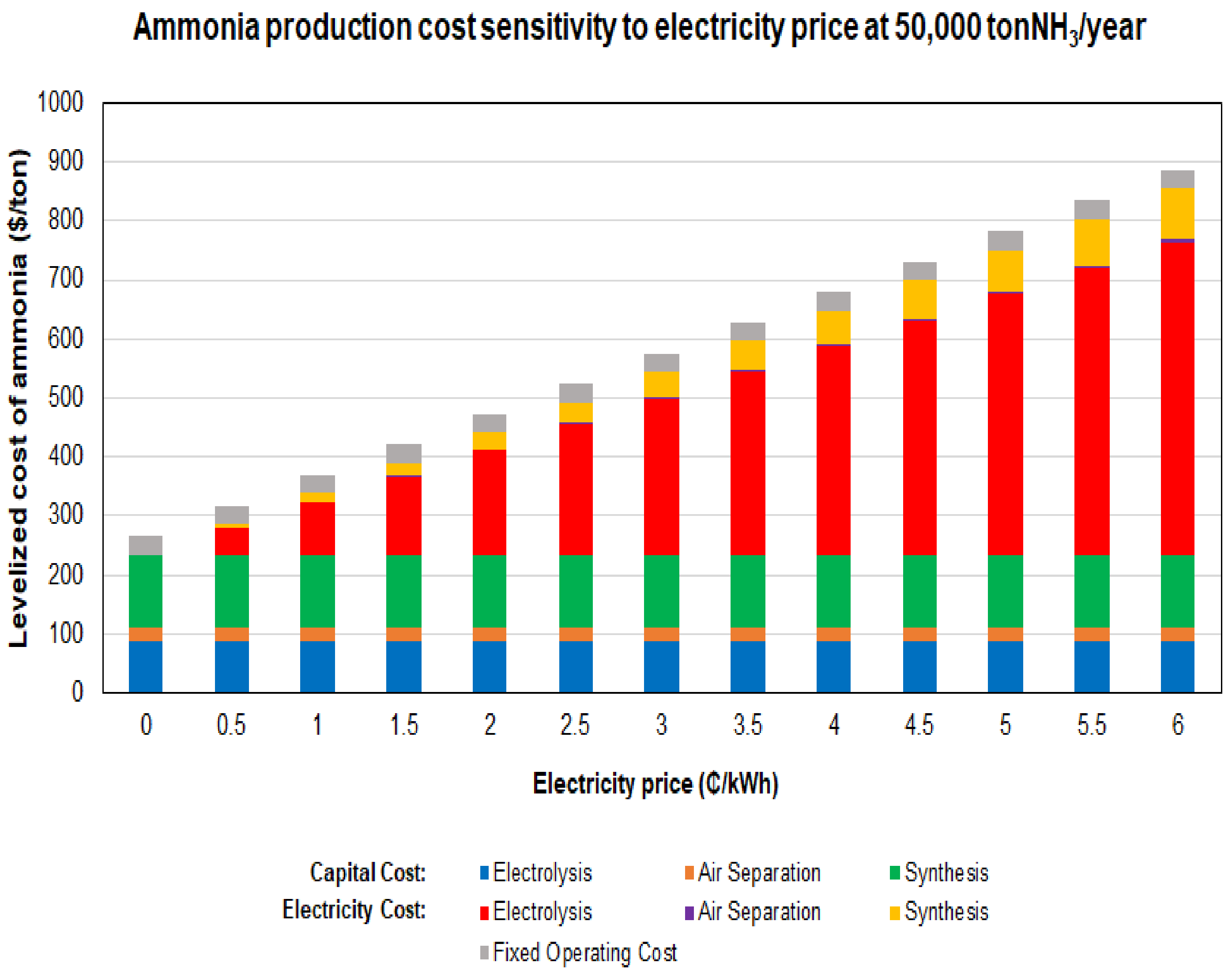
- Conventional supply + local production based on available wind power
- Modular deployment for economies of volumes (0.9 exponent)

Configuration at $650/t Conventional Price



Renewables incorporated via distributed deployment of ~10,000 ton/y modules

Estimated cost of ammonia per ton at regional-scale with new distributed production technology



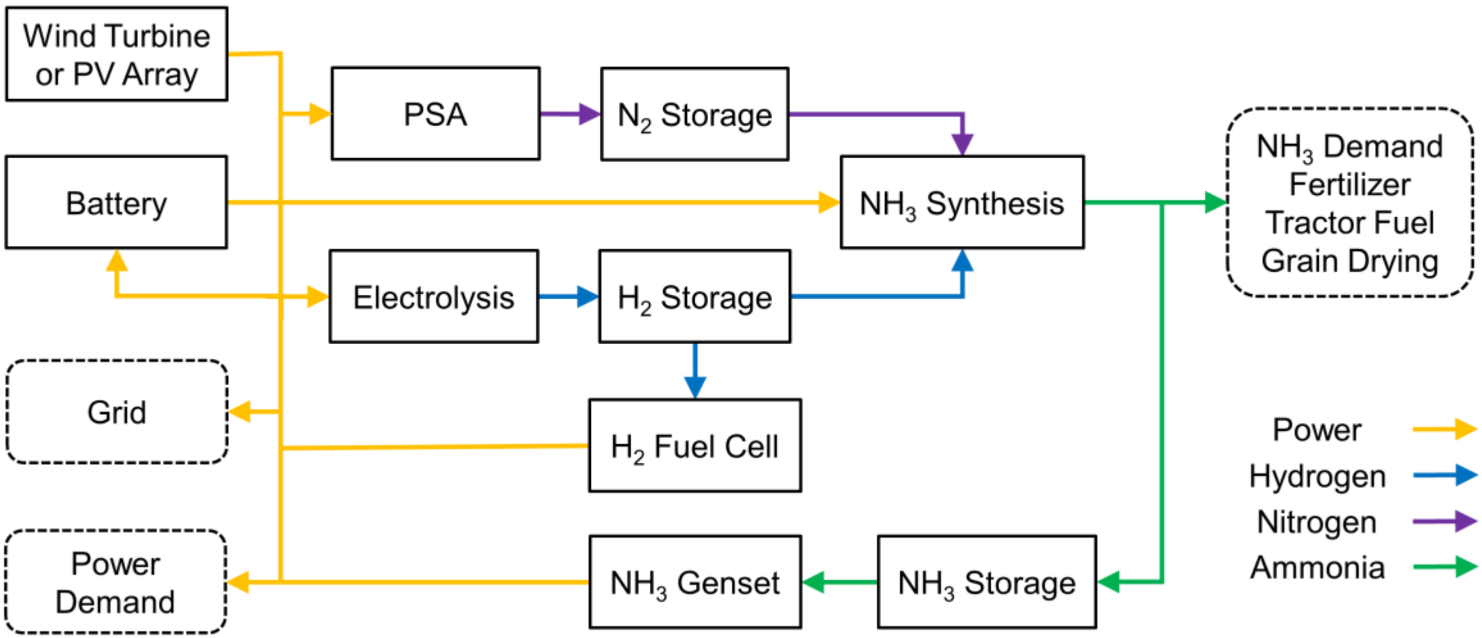
Palys et al. (2019)

Ammonia-Enabled Sustainable Energy and Agriculture

Palys et al. (2019). *Chem. Eng. Process., 140*, 11-21.

In addition to energy storage, renewable ammonia at farm scale for:

- Fertilizer
- Tractor and grain drying fuel



Implementation case study using Morris, MN data

- Two 1.65 MW wind turbines
- Annual average power demand: 985 kW
- Ammonia demand (fertilizer & fuel): 40 ton/year

Emissions avoidance cost of $18/ton$CO_2$

Opportunity: Other Green Fertilizers

- Manure – increased emphasis on livestock production – perhaps further processed to recover nutrients or provide more available, less harmful formulations (e.g. N2Applied)
- Ammonia nitrate and aqueous ammonia production via non-thermal plasma (e.g. FarmGenN)
- Nutrient capture from agricultural and other forms of run-off and wastes
- Biochars and other nutrients from gasification and pyrolysis processes
- Seaweed and algae production and harvest
- Phosphorus recovery (peak phosphorus?)
  - As a note, there is a finite supply of rock phosphorus in the world and there may be opportunities to develop phosphorus production / recovery systems.
- Micro-nutrients such as sulfur, zinc, and boron have high values but much lower quantities are applied to crops

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- University of Minnesota College of Food, Agricultural, and Natural Resource Sciences (CFANS)
- Clean Energy Resource Teams (CERTS)
- Electric Power Research Institute (EPRI)

Conclusions:

- ✓ The US has significant market demand for agricultural fertilizers
- ✓ Conventional nitrogen fertilizer production represents approximately 1% of all global greenhouse gas emissions
- ✓ The carbon-intensity of grain, meat, milk, ethanol, and other agricultural products is highly influenced by the conventional production of nitrogen fertilizer
- ✓ In the absence of GHG reduction policies or market pressures, price targets for green or zero- or low-carbon fertilizers need to be on par with conventional fertilizer prices
- ✓ The distributed nature of renewable electricity generation favors the distributed production of green nitrogen fertilizer over centralized plants
- ✓ US nitrogen fertilizer market could be supplied 100% by adding ~50,000 MW of wind capacity
- ✓ Coupled with the declining costs of wind and solar generation, green ammonia production technologies are becoming cost competitive

Resources and Contact Information:

https://extension.umn.edu/crop-production#nutrient-management

https://wcroc.cfans.umn.edu/research-programs/renewable-energy/ammonia

https://www.nass.usda.gov/

https://www.fertilizer.org

https://www.ammoniaenergy.org/

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